THE NAVAL AIR SYSTEMS COMMAND

ELECTROMAGNETICS BRANCH

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AIRFRAME ELECTRICAL GROUNDING REQUIREMENTS PROGRAM

FINAL REPORT

AIR ~~5161~~-1000

Volume 1

LEAD INVESTIGATING ACTIVITY: NAEC
DTB26R80-1186

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ABSTRACT

An engineering investigation of airframe [illegible] grounding requirements, methods, and facilities has been made to resolve present conflicts [illegible] a basic grounding philosophy. Based on an evaluation of data, a technical committee [illegible] that it is necessary to continue and extend the use of airframe electrical grounding [illegible] of both personnel safety and equipment protection.

The committee also concluded that the present static ground impedance requirements are too stringent, resulting in unnecessarily costly grounding systems. Aircraft mooring padeyes located on parking aprons measured less than 10,000-ohm resistance to earth and are recommended as a static ground attachment point. The use of mooring padeyes as static grounds has two major advantages: it will increase the number of static ground points available, and it will eliminate the need for future installation of expensive, separate grounding systems in all areas except maintenance locations.

It was also found that for external power grounding, the existing requirements are vague and may be unsafe when not based on an analysis of total power requirements and circuit protection levels. Additional guidelines are recommended for electrical ground systems when external power is connected to the aircraft or used near it.

Some problems which were considered relevant to the grounding study were investigated even though the resolution of these problems was beyond the scope of the program. These problem areas are cited herein to document pertinent data and to indicate possible direction for future efforts. The areas include hardware, power fault systems, fuel additives, specifications and documentation, and composite material, each bearing on aircraft safety with respect to electrical hazards.

The results of the airframe electrical grounding program provide a documented technical base for a naval aviation electrical grounding philosophy. These results can be applied to resolve existing conflicts, to recognize necessary deviations and waivers, and to standardize grounding concepts, techniques, evaluation methods, and documentation. These data, observations, and conclusions also provide an accurate input for present and future development programs to ensure that proper airframe electrical grounding requirements are imposed in the initial equipment specification.

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1.0 INTRODUCTION.

1.1 Background. Airframe electrical grounding has been mandated to prevent personnel hazard and equipment damage. The number and complexity of service operations and the variability of electrical hazard effects, however, have resulted in considerable confusion in grounding procedures. In addition, some electrical hazards (e.g., internal sparking in an all-metal fuel tank or radio frequency (r.f.) arcing) cannot be corrected by grounding. Such hazards raise doubts concerning the overall effectiveness of grounding and questions on the economical value of present grounding systems.

In response to the above, the Electromagnetics Branch, AIR5181, Naval Air Systems Command (NAVAIRSYSCOM), Washington, D.C., has performed an investigation and technical evaluation of airframe electrical grounding practices and requirements. This program has been designated as the Airframe Electrical Grounding Requirements Program. Its objective has been to establish a basic grounding philosophy for naval aviation.

1.2 Assessment of Present Practices. As part of the pre-program planning, a cursory survey of existing specifications and procedures verified the extent of concern with airframe electrical grounding practice. It was found that:

a. There are many differing values of grounding resistance specified for protection from static discharge hazards; requirements vary from 10 to 100,000,000 ohms.

b. The requirements for power ground are being confused with static ground requirements. The generally recommended values of 10 and 25 ohms are inadequate compromises for either static or power ground systems.

c. A fueling transfer problem of potential ignition of vapors inside fuel tanks (being adequately addressed by petroleum handlers) is being confused with the need to ground aircraft during all servicing for personnel safety and equipment protection.

d. There was little information on aircraft and aircraft grounding facility characteristics available for an engineering assessment of requirements. The electrical values of aircraft tire resistance, airframe capacitance, the condition of grounding hardware, the degradation of ground points with time, and the grounding scenarios were all in question.

These areas were all afforded special attention during the ensuing investigation.

1.3 Program Definition. The program established an overall plan of action, two investigation teams to gather data, and a technical committee to provide direction and data evaluation. Major activities of the investigation teams included:

a. Land and carrier on-site surveys

b. Technical literature survey

c. Requirement documents survey

d. Speed letter questionnaire survey

e. Incident report survey

f. Tests of airframe electrical characteristics (both on-site and under controlled conditions at Naval Air Engineering Center (NAEC), Lakehurst, N.J.

g. Interviews with various experts and other interested parties

Data obtained during the investigation activities were documented in a series of interim reports. Various subcommittees were then established to formulate, based on the investigation data, technical requirements which are the foundation for the recommendations of this report.

Further details of the program structure are presented in Program Particulars, paragraph 5.0.

1.4 Program Report. The final program task, a report of findings, is contained in two volumes. Volume I, presented herein, contains:

a. A detailed discussion of data (paragraph 2.0)

b. Recommendations and conclusions (paragraph 3.0)

c. A summary of program data for reference (paragraph 4.0)

d. Details of the program structure (paragraph 5.0)

Volume II, retained by AIR5181, records all data obtained during surveys and tests and the procedures used to obtain the data.

2.0 RESULTS AND DISCUSSION.

2.1 Evaluation Methodology. Data resulting from this investigation were analyzed and evaluated to identify applicable electrical hazards which would be reduced by the use of airframe electrical grounding. An electrical hazard was defined as a condition posing the potential for serious shock or injury to personnel or the potential for damage/upset to equipment.

The investigation data consist of:

a. Measurement on airframes and grounding systems

b. On-site observations of conditions and procedures

c. Information obtained during the technical literature and incident report survey

d. Information obtained during interviews with researchers in this field

Analysis of this information established the scope of the hazard. The identified hazard was then considered in terms of those elements required to ensure its occurrence (e.g., spark energy content, component damage threshold, etc.) and was assessed in particular scenarios. To confirm the validity of a hazard, it was further compared with both observations made by the survey teams and comments contained in incident reports. A valid hazard was ranked by considering the probable occurrence rate in a scenario and the probable extent of personnel injury and/or equipment damage.

The effectiveness of an electrical ground in eliminating a hazard was also considered. The type of ground required was compared with the test and survey data results (e.g., aircraft electrical resistance to ground, electrical capacitance, charging mechanisms etc.) to establish the technical requirement needed to void the posed threat. Each technical requirement was supported by technical data, as opposed to administrative requirements, specifications, or instructions, which may not be based on a technical need.

If a technical requirement exists (that is, if an action is required for safety by the observed data), it was formulated and used as a basis for the recommendations of this report. Every effort was also made to factor in grounding hardware and operational cost in the formulation of technical requirements; however, safety was maintained as the prime requirement. In all cases where a reasonable doubt existed in the safety of an operation in terms of electrical hazards due to lack of a ground connection, the requirement for grounding was recommended.

2.2 Scenarios. The following aircraft evolutions or scenarios were considered in the evaluation:

a. Stores handling (including ordnance)

b. Maintenance (flight line and hangar)

c. Fueling

d. Parked

Potential hazards considered during each scenario were:

a. Static electrical shock to personnel

b. Power system electrical shock to personnel

c. Ordnance misfire and/or inadvertent ordnance or store release

d. Fuel vapor ignition

e. Damage or upset to electronic subsystems

2.3 Energy Sources. Each of the hazards cited above is initiated by the release of electrical energy. The source mechanism and source magnitude of the electrical energy is, therefore, critical in assessing the possible occurrence of a hazardous situation. The following energy sources were considered during the scenarios described above:

a. Static

(1) Triboelectric

(2) Fuel flow

(3) Induced

(4) Friction

b. Power

(1) Ground fault

(2) R. F. electromagnetic energy

(3) Lightning

Each source is defined and evaluated in the following paragraphs.

2.3.1 Triboelectric Effects. These effects are generally associated with precipitation static in an airborne vehicle. High static voltages, however, can result from interaction at the contact surfaces of various materials in any type of relative motion; e.g., wind-blown snow or dust particles striking a parked aircraft. No measurements were found in the literature for electrical current values due to triboelectric effects on parked aircraft. However, using linear extrapolation of airborne data, [15] a conservative estimate of 30 microamperes (μA) electrical current for a moderate, wind-blown dust situation is possible.

2.3.2 Fuel Flow. Each fueling of an aircraft provides the mechanism for a recurring electrostatic energy source. The surface phenomena between the moving fuel and fuel filter, hose, and other surfaces result in charge separation. Since fuel is normally an excellent insulator, separated charges are easily removed by the flowing fuel to a distant location. If no electrically conductive return path is available, the charge accumulates on metallic surfaces and represents a high potential energy. As the accumulation of charge continues, sufficient electrical potential is generated to cause an arc across insulating barriers. Through such arcing, the charge establishes the path necessary to return to its source, where it is neutralized.

Studies by Naval Research Laboratory (NRL), German Airforce, United States Air Force (USAF), and others have provided data on the magnitude of voltages and current which might be encountered during the fueling process. Field strengths generated by this process may range to 500 kilovolts/meter (kV/m); thus at a centimeter distance 5-kV potential may be present.[1,2,3] The 500-kV/m field is normally confined to the fuel tank interior. However, depending on the locations of the separated charges and the degree of electrical isolation of the aircraft, fields of this intensity may appear on the exterior as charge bleed-off occurs. The resulting voltage on the exterior of the tank is dependent on the physical configuration and could reach breakdown or arcing level near sharp edges. Measurements after fueling an A-4 aircraft at NAEC provided values of 2.5 kV (Table XI, page 33).

Current flow due to fuel flow was measured at levels of 7.5 μA (Table XI, page 33). A reported maximum value of 13 μA[4] was therefore considered reasonable for use in analysis.

In the area of fueling, this investigation addressed the electrical effects on the outer surface of the fuel tank or aircraft skin and the electrical currents through interconnecting bonds or grounds. Electrostatic effects in the interior of the metallic fuel tank cannot be corrected by airframe grounding. The petroleum-handling groups have provided devices such as relaxation tanks and anti-static additives to reduce the hazard of electrostatically caused explosions in the tank interiors, and they are continuing investigation of this problem.[3][5]

2.3.3 Induced Charge. The presence of an electric field between an active storm cloud system and the earth will result in large induced charges on aircraft. A sudden change in the field (e.g., a distant lightning strike) can release this charge, resulting in potentials of 40 to 60 kV from airframe to ground.[6] This effect should not be confused with the lightning strike itself since there is a significant difference in power levels.

2.3.4 Friction. Similar to triboelectric and fuel flow static phenomena, the movement of the interface between synthetic cloth materials, especially in cold climates, can generate potentials as high as 27 kV.[7] Explosions due to this phenomenon are a matter of record.[8] The 27 kV value is used herein as representative of the worst case static electricity friction hazard levels produced by servicing personnel.

2.3.5 Ground Power Fault. The large number of incident reports citing ground faults have led to their consideration herein. Ground power connection becomes hazardous when the high voltage side of an external power connection is brought into contact with the airframe or when the power cable neutral is faulty. These faults often occur through miswiring of the connector plug, although component failure has also been responsible. In such an occurrence, the entire airframe is at power line potential, 120 to 220 volts, and may be capable of supplying currents as high as 200 amperes. The possible power levels set this hazard apart in terms of ground requirements. Due to high power capabilities, ground fault protection and power system grounding requirements are considered to be in a category separate from static grounding.

2.3.6 R. F. Energy. Although induced r. f. energies are a major hazard, neither test data nor analytical results indicate that grounding will provide any dependable amount of protection in this area. Therefore, no grounding recommendation on this threat is made herein.

2.3.7 Lightning. Lightning discharge through an aircraft to earth is an extremely variable phenomenon. Voltage as high as 0.5 million volts and currents from 200 to 200,000 amperes are cited in the literature. At such high levels, grounding will not afford the degree of protection or confidence factor attained for static electric protection. Nevertheless, a safety ground will aid in protecting personnel and equipment to some extent, especially for the lower energy strikes.

2.3.8 Summary. In summary, the levels of electrostatic and electrical energies considered are tabulated below (Table I, page 6).

2.4 Electrical Parameters. When energy sources are considered in terms of voltage or current, the electrical characteristics (i.e., tire resistance to ground and airframe capacitance to ground) are required to establish time duration and other parametric relationships (e.g., current to voltage and current or voltage to total energy). Aircraft characteristics were obtained during a physical survey of Navy, Air Force, NATO, and the carrier CVN-69 facilities and by specific tests performed at NAEC, Lakehurst, N.J.

Table I

Summary of Electrical Energy Sources

Source	Level: Voltage	Level: Current
Triboelectric	–	.03 mA
Fuel Flow	2.5 kV	.013 mA
Induced Charge	60 kV	–
Friction	27 kV	–
Ground Power Fault	220 V	200 A
R.F. Induced	Grounds Not Applicable	
Lightning	500 kV	200 kA

Airframe electrical parameters interact with charge generation mechanisms and thereby establish the actual hazard levels and time duration for these hazards. Airframe capacitance to earth and airframe resistance to earth are most relevant. Capacitance establishes the total charge stored due to a particular potential and the time factor required to dissipate a charge from a surface through a particular resistance. Resistance establishes the voltage associated with known current flows and the time factor for charge reduction when the capacitance is known. Resistance was found to be the more variable parameter.

Values of from 1 kilohm (kΩ) (Table IV, page 26) to 100 megohms (MΩ) (Table VIII, page 30) were measured. However, the 100 MΩ value was measured on a carrier deck which had an epoxy nonskid surface as an additional insulation layer. The next lower value, encountered at several locations, was 40 MΩ (Table IV, page 26). Capacitance was more consistent, ranging from 0.002 to 0.005 microfarads (μf) (Table XI, page 33) measured over a wide range of aricraft types and ground plane materials.

In addition to the characteristics of the aircraft, the values of the human bodies' electrical parameters are also needed. Values of 500 picofarads (pf) capacitance and 50 to 1500 ohms resistance are representative values for analytic purposes.[7][8][9]

The pertinent electrical characteristics are summarized in Table II (page 7); the aircraft measurements are detailed in paragraph 4.0, on Table XI (page 33), and in Volume II.

2.5 Hazard Threshold. The third variable needed for analysis is the threshold for injury or damage due to electrical effects.

2.5.1 Fueling. The literature survey established that the minimum energy threshold for ignition of fuel is accepted as being 0.25 millijoule (mj). [1][2][3][4][5]

2.5.2 Stores. A level of 35 mj is generally cited as the potential danger level during stores and ordnance handling and has been used herein.[5][10] The ignition of electroexplosive devices (EED) in various actuating mechanisms is the most common danger area.

Table II

Electrical Parameters

Aircraft Capacitance	–	0.002 to 0.005 μf
Aircraft Resistance	–	1.0 kΩ to 40 MΩ
Body Capacitance	–	500 pf
Body Resistance	–	50 to 1500 ohms

2.5.3 Shock to Personnel. There are two possible sources of injury to personnel from shock: (a) involuntary reflex movements which can result in injury due to secondary effects, such as falling; and (b) electrical effects which result directly in injury. According to Lee, reflex action appears in the area of 10 to 30 mj (1 to 3 mA across 10,000 ohms); a representative voltage would be approximately 50 V (30 mj and 1500 ohms).[9] The threshold level for potentially lethal shock was established as 30 VAC and 45 VDC[11] at energy levels of 600 mj AC to 1.35 joules DC.[9]

2.5.4 Equipment Damage Level. The threshold level for equipment damage is a function of dielectric breakdown (high voltage effect) and/or high temperature damage (high power effect). In the studies reviewed, 1 mj caused upset when directly injected into sensitive circuits.[12] However, since direct injection is unlikely, a coupling factor of approximately 10 was assumed to establish a minimum threshold of 10 mj for the practical lower limit of sensitive equipment upset. Damage levels were taken as 35 mj, comparable with ordnance thresholds (paragraph 2.5.2). It is recognized that much greater sensitivity is possible; however, in those cases, the burden of protection should be placed on the equipment designer.

2.5.5 Summary of Hazard Threshold Levels. There was some minor variation in threshold values throughout the literature surveyed. However, agreement was generally found to be within an order of magnitude. For the purposes of this report, the following values were used:

Reflex action shock:	10 mj or 50 V
Shock to personnel power:	600 mj (AC) or 32 VAC or 3 mA 1.35 joule (DC) or 45 VDC or 3 mA
Stores and equipment	
EED ignition:	35 mj
Component damage:	35 mj
Component upset:	10 mj
Fuel vapor ignition:	0.25 mj or 40 kV

2.6 Other Physical Considerations

2.6.1 Regardless of energy sources, no fuel ignition hazard is present unless there is a specific fuel-air vapor mixture present. It has been observed on site by the survey teams that fuel spills are quite common and provide the necessary vapor source. Since an aviation gasoline, JP-4, or JP-8 vapor mix varies from too rich at the point of the spill to too lean at some distant point, the proper mix for ignition will be present between these points. A second source of vapor is vented from fixed-volume tanks during the fueling process. Again, this vapor is leaned by mixing with air until an explosive mix is reached, possibly at some point external to the fuel tank. These considerations establish that a dangerous fuel-air vapor mix may be present during the scenarios.

2.6.2 A second consideration is the type of fuel used. JP-4 is considered more hazardous than JP-5 due to the lower flashpoint of JP-4. According to the results of the Naval Airbase Questionnaire (Table X, page 32), 56% of the stations responding use JP-4 fuel in at least part of their operations. The possibility of JP-4 being present as fuel vapor greatly increases the potential hazard during the various scenarios. In addition, the practice of switch loading (the mixing of two different types of fuel during fueling or defueling operations) often results in a mixture more dangerous than either type individually, further increasing the risks during the fueling operation.

2.6.3 The bonding practices and hardware configurations observed in the field by the investigation teams where also a source of considerable concern. As used herein, electrical grounding is the provision of a conductive path between the airframe and ground or between the refueling vehicle and ground. Bonding is the provision of a conductive path between the airframe and the refueling vehicle. In the case where grounding and bonding are both used, a triangular system is established with electrical paths between the ground point, the vehicle, and the airframe. In the triangle system, the ground path supplies a backup or alternate path in parallel with the bonding cable. This alternate path is valuable since it was noted during field surveys that cables were often connected by means of alligator clips to painted, corroded, or non-conductive composite material surfaces or to isolated metallic components. In each such case it was doubtful that bonding was adequate, and in some cases it was obvious that one or both return paths were not satisfactory. The use of proper electrical grounding is vital in such situations to provide a dependable alternate path for electrical currents and, thus, to ensure safe operation. It should be noted that due to conflicting specifications and incompatible connectors (phone jack vs. alligator clip), operators often did not have an option to correct these situations.

2.6.4 The use of alligator clips was also observed to have damaged and, in some cases, completely severed the bonding straps in such locations as the fuel port doors, bomb bay doors, or nose wheel doors. These straps are required for electromagnetic compatibility and lightning protection. Their integrity must be maintained for safety and proper system operation.

2.6.5 Foreign object damage (FOD) from grounding system hardware is an additional threat to equipment. The most common grounding receptacle uses a 4- to 5-ounce brass cover with a 9-inch length of window sash chain to fasten the cover to the receptacle housing. It was observed that both the cap and chain may become loose. At several locations they were cut off and disposed of immediately after installation. The FOD aspect must be eliminated in any consideration of the electrical grounding hardware.

2.6.6 During carrier operations, the aircraft are normally moored to the metal deck by means of metal chains. No grounding problems were anticipated. However, during the survey aboard the USS Dwight D. Eisenhower (CVN-69), an aircraft-to-ground resistance measurement of 40 kΩ was recorded. This measurement was taken on an F-14 aircraft which was secured to the flight deck by 12 tiedown chains for a period exceeding 24 hours. Subsequently, tiedown chain resistance was measured and found to be 5 MΩ. Other aircraft, if tied down with just 6 of the 12 chains used on the F-14, could show much higher resistance to ground. While the resistance of new chains measures less than 0.5 ohm, most chains showed evidence of surface corrosion, indicating a much higher average resistance. The tiedown chain cannot be relied on for aircraft electrical grounding as recommended in Naval Air Training and Operating Procedures (NATOPS) manuals. Hence, positive, reliable grounding systems are not available in the fleet with present hardware configurations.

2.6.7 Standardization of grounding hardware must also be considered. The present North Atlantic Treaty Organization Standardization Agreement Requirement (STANAG) NO. 3632 covers only the design of the connector attached to the grounding/bonding wire or fuel hose at the aircraft end. Thus, it is left to the country owning the aircraft to provide a suitable matching receptacle, ground cable, and ground point. In addition, many visiting aircraft carry their own grounding wires.

The survey observed that different grounding methods are used in each country. The Royal Air Force uses a nut and bolt or a clamp device, the Italian Air Force uses a spring-loaded connector with a built-in switch, and the Netherlands uses a heavy alligator clip to a short piece of flexible braid. The United States Air Force has developed a heavy alligator-type clip. The United States Navy relies upon steel tiedown chains aboard a carrier and a variety of clips, cable arrangements, or chains at shore bases. Standardization throughout the aviation community is necessary to achieve safe operations.

2.6.8 The electrical resistivity characteristics of the parking apron or carrier deck are a most critical factor in determining the need for an aircraft ground. The nonskid epoxy surface used on carrier decks can isolate a system with a resistance of 100 MΩ (Table VIII, page 30), thereby ensuring that electrical charge, if present, will be trapped and will pose a potential hazard.

During the survey of NATO facilities, locations were visited where the service area in front of the hangars had a special coating intended to camouflage from infrared-seeking missiles. This coating also produced an extremely high, > 100 MΩ electrical isolation for the aircraft. Since rigid electrical ground requirement procedures are enforced, this isolation is not a problem for the host country; however, a visiting aircraft, without proper and compatible grounding configuration, would be in jeopardy.

A more common concern is the use of asphalt (blacktop) as an aircraft parking apron surface. While somewhat variable, this material generally provides a high level of isolation and, therefore, presents a potential hazard if positive grounds are lacking.

2.6.9 The maximum allowable levels of ground resistance are derived from two requirements: the requirement to discharge static electricity and the requirement to provide an adequate fault current return path in the event that external, earthed neutral power is applied. In considering recommendations, it is also necessary to address feasibility, cost effectiveness, the requirements of existing specifications, and operational factors.

2.6.9.1 The static discharge requirement is based on the maximum resistance which still allows charge to bleed off to a safe level in a reasonably short duration of time and on maintaining a safe voltage under steady discharge currents. Extremely short duration discharge characteristics (microsecond region) are governed by configuration inductance, a parameter which cannot be reliably controlled by grounding. A longer duration discharge, however, is related to the ground resistance by

$$R = \frac{t}{C \ln \frac{E_i}{E_s}}$$

where R = ground path resistance

t = discharge time

C = electrical capacitance

E_i = initial voltage

E_s = safe voltage

A discharge time (t) of 0.2 second is chosen on the basis that heart action discoordination (fibrillation) has this duration as a threshold level.[14] Aircraft capacitance is 0.005 μf, E_s is 30 V, and the initial voltage source can range to values of 60 kV for atmospheric induced charge (see paragraphs 2.3 through 2.5). Therefore,

$$R = \frac{0.2}{(0.005 \times 10^{-6}) \ln\left(\frac{60 \times 10^3}{30}\right)} = 5.26 \times 10^6 \text{ ohms.}$$

This value is easily obtained by using aircraft mooring padeyes (Table VI, page 28), but it will not be obtained with any certainty if aircraft tire resistance alone is relied on to provide a ground path (Table IV, page 26).

The restriction on grounding requirements is still more severe if discharge currents are considered. The highest discharge current considered is 0.03 mA due to triboelectric effects. To maintain a 30-V safety level at the airframe, the ground path impedance must be less than

$$R = \frac{E_s}{I} = \frac{50}{3 \times 10^{-5}} = 1.6 \times 10^6 \text{ ohms.}$$

In consideration of both the above exam, les, 1.0 MΩ is an adequate maximum resistance for ground path return. To establish a satisfactory recommendation, the following considerations were also addressed:

a. Due to the wide variability of parameters, the potential for damage, and the threat to personnel, wide safety margins are required.

b. All field measurements of mooring padeyes were well under 10 kilohms (kΩ).

c. The 10-kΩ resistance value is widely accepted as a standard for static ground resistance in many (but not all) specifications.

2.6.9.2 Power introduced from an external source complicates the selection of a ground return limit. The maximum allowable ground resistance is dictated by the requirement that sufficient current flow to trip power circuit protective devices under ground fault conditions (paragraph 2.11.1). The trip time (time to open circuit), which is a function of the ground path resistance for ground faults, must also be considered. Personnel safety requires that the ground path resistance be low enough to allow a 500 to 600% overload current with a trip time of approximately 0.2 second.[9]

Thus, a 120-V, 50-A service requires a ground path return resistance of 0.5 ohm for safety under ground fault conditions. This value is attained in many cases (Table V, page 27). However, it is also evident from Table V that there are locations which do not provide 0.5-ohm ground resistance and thus are limited in the safe maximum load which can be handled. As an example, a 120-V source with 10 ohms in the return path and a 500% overload trip level for 0.2-second response time is limited to a service current of

$$I = \frac{E}{(R)\,(\text{OVERLOAD})} = \frac{120}{(10)\,(6)} = 2\text{A.}$$

Shortening the trip response time only increases the occurrence of nuisance trips to an unacceptable level. The requirement for a very low resistance ground path remains and must be considered with other parameters in the design of each individual installation.

2.7 Analysis. The basic purpose of the previous subparagraphs within this section has been to establish the data which verify or disprove the hypotheses that (a) an electrical hazard exists and (b) grounding will eliminate or reduce this hazard. The first hypothesis (hazard exists) is assessed by a comparison of energy source levels with hazard threshold levels and scenario particulars. The second hypothesis (grounding reduces hazard) is assessed by considering the extent to which application of an electrical ground alters the available energy, location of discharge, or duration of hazard. The results of the analyses are summarized in paragraph 2.7.3 following the detailed analysis below.

2.7.1 Source Magnitude and Hazard Threshold Level. The magnitude of potential energy sources is compared with hazard threshold levels to identify those combinations which could result in a hazard.

a. *Triboelectric Source.* As noted in Table I (page 6), an upper bound of 0.03 milliampere (mA) defines the worst case triboelectric energy source. Since in an ungrounded aircraft this current flows from earth, through the aircraft tire resistance, to the airframe, and thence to the snow, dust, etc. causing the effect, the potential between airframe and earth is determined almost entirely by the tire resistance. While laboratory measurements of tire resistance in the 100-MΩ range have been made,[13] the worst case measured value of 40 MΩ, obtained in the field, is used here to compute airframe potential of

$$V = IR = (0.03\ \text{mA})(40\ \text{M}\Omega) = 1200\ \text{V}.$$

Using a value of C = 0.005 μf from Table II, the energy level, U, could reach

$$U = \tfrac{1}{2}CV^2 = \tfrac{1}{2}(0.005\ \mu\text{f})(1200\ \text{V})^2 = 3.6\ \text{mj}.$$

The values of U and V above exceed the hazard threshold levels of paragraph 2.5.5 for fuel vapor ignition and nonlethal shock to personnel.

b. *Friction Source.* The Table I (page 6) value for the worst case static voltage level is 27 kV. In addition, energy levels may range as high as 0.18 joules.[7] Comparison with the hazard threshold values in paragraph 2.5.5 shows that the thresholds for reflex level shock to personnel, fuel vapor ignition, and stores or equipment damage are exceeded.

c. *Fuel Transfer.* During fuel transfer the separation of charge can result in electrical current of 13 μA. Also, measurements summarized in Table XI (page 33) indicate that at the termination of a fueling operation, after bonding straps are disconnected, a completely isolated aircraft may exhibit static voltage levels of as high as 2.5 kV. The 13-μA current flow due to fuel transfer can result in voltages of

$$V = IR = 13\ \mu\text{A} \times 40\ \text{M}\Omega = 520\ \text{V}$$

if the only return path is through the airframe. While this condition will not exist when the aircraft is properly bonded to the fuel supply system, both improper connection of bond clips (to painted or nonmetallic surfaces) and poorly maintained bonding cables (loose and/or rusted connections) were observed during the field survey. Thus reliance on the bonding strap alone could, if the bond is faulty, produce 520 V between airframe and earth or refueler. This represents an energy level, U, of

$$U = \tfrac{1}{2}CV^2 = \tfrac{1}{2}(0.005\ \mu f)(520\ V)^2 = 0.68\ mi.$$

In the case of an electrically isolated aircraft, after disconnection of the bond the available energy can reach

$$U = \tfrac{1}{2}CV^2 = \tfrac{1}{2}(0.005\ \mu f)\ (2.5\ kV)^2 = 15.6\ mj.$$

These values exceed the threshold hazard values for ignition of fuel vapor. Therefore, fuel vapor ignition should be considered during fuel transfer. For the electrically isolated aircraft, fuel vapor ignition, equipment upset, and reflex shock reaction by personnel must be considered.

d. *Induced Voltages.* Table I (page 6) establishes 60 kV as the source level due to charge induced by storm activity. Energy levels may then reach

$$U = \tfrac{1}{2}CV^2 = \tfrac{1}{2}(0.005\ \mu f)(60\ kV)^2 = 9\ joules.$$

These levels exceed threshold values for all hazards.

e. *Power Systems.* The Table I values of 120 V and 200 amperes exceed all threshold levels of paragraph 2.5.5 for all hazards.

2.7.2 Time Duration Considerations. Some of the phenomena cited in paragraph 2.7.1 above are transient in nature. Knowledge of their duration is necessary to assess them as realistic hazards. Induced voltages, friction voltages, and voltage buildups following fueling (see Table XI, page 33) were considered transients.

Using the ungrounded aircraft resistance of 40 MΩ, an aircraft capacitance to ground of 0.005 μf, and a safe voltage limit of less than 30 V, the following time durations were computed from:

$$t = RC \ln\left(\frac{E_i}{E_s}\right)$$

where t = time to reach E_s after removal of source

R = aircraft resistance to ground

C = aircraft capacitance to ground

E_i = initial (source) voltage

E_s = safe voltage level

Transient Source	E_i Source Magnitude	Time to E_s
Friction	27.0 kV	1.36 sec
After-fueling potential	2.5 kV	0.88 sec
Induced	60.0 kV	1.52 sec

Any transient is objectionable from a safety standpoint. Heart action discoordination (fibrillation) threshold levels have time durations as low as 0.2 second.[14] Thus the duration of even the shortest of the three transients considered is unacceptably long.

2.7.3 Hazard Assessment. Ungrounded aircraft must be considered to be in jeopardy from the indicated energy souces since at least one and generally more than one hazard threshold level is exceeded during each scenario. These results are summarized in Table III below.

Table III

Potential Hazard Relationship to Energy Sources and Scenarios

Scenario	Energy Source				
	Tribo	Friction	Fuel Trans	Atmospheric Induced Fields	External Power System
Maintenance	AD	ADE	–	ADE	BD
Fuel	AD	ADE	ACDE	ACDE	BCDE
Stores Handling	AD	ACE	–	ACE	–
Park	AD	ACDE	–	ACDE	–

Hazard Present:

- A – Static shock to personnel
- B – Power shock to personnel
- C – Ordnance EED/stores misfire/release
- D – Fuel vapor ignition
- E – Electronic equipment damage

The possibility of these hazardous events occurring is ensured by the physical data available. However, each event is dependent on a number of factors which may occur simultaneously only very rarely (for example, the refueling of an aircraft with 40 MΩ impedance to earth, a fuel spill, and an electrical spark located at the right point in the volume of fuel vapor or misted fuel to cause ignition). In any single one-time event, such as an aircraft repair or refueling operation, consideration could be given to the fact that hazardous combinations appear so seldom that they may be neglected. However, when consideration is given to the number of naval aircraft involved, the rapid tempo of operations, the fact that these are military operations (not always conducted under ideal conditions), the high cost of equipment, and the threat to personnel safety, electrical grounding for safety becomes an imperative requirement. Electrical airframe grounding, like safety belts in automobiles, is statistically dictated by, among other things, the vast numbers involved.

2.7.4 Effects of Grounding. In each of the scenarios considered, the use of a proper ground connection will ensure that the airframe is maintained at the same potential as the ground point for those sources considered except in the case of external power systems (see paragraph 2.11.1). In addition, since the airframe resistance to ground is now reduced to near zero, the duration of such effects as induced voltages is reduced to fractions of a millisecond.

As an additional advantage, the use of a proper grounding procedure will ensure that any arcing or electrical discharges associated with the act of connecting grounds will take place at the ground point rather than near the airframe.

2.8 **Documentation.** The major categories of documentation reviewed were:

a. National Safety Standards

b. Fleet Safety Standards

c. NATOPS Aircraft Publications

d. Applicable Design Standards

e. Military Standards

f. Military Specifications

g. Navy Instructions

h. Navy Regulations

i American Petroleum Institute (API) Publications

j. National Fire Prevention Association (NFPA) Publications

k. US Air Force Directives

During review of these documents, it became clear that there were major conflicts in the philosophies and requirements detailed in the various documents.

Documentation cited below illustrates the confusion and conflict in the literature. It should be noted that conflicts are often apparent within the same organization; e.g., the National Fire Prevention Association recommendation for a maximum static ground varies from 10 kΩ to 1 MΩ.

- NFPA document #407, "Aircraft Fuel Servicing 1975," states in paragraph 2-3.2.4: "Maximum Resistance and Grounding Electrodes – Although a resistance as high as 10,000 ohms is acceptable in a static grounding electrode, it will usually be found that a much lower resistance is readily attainable."

- NFPA document #77, "Static Electricity 1977," states in paragraph 3-1.3: "Because the leakage currents are extremely small a resistance to ground of 1 megohm (10^6 ohms) is adequate for static grounding."

- NAVORDNOTE 8020 – ORD 048 – 29 MAR 70 – "GROUNDING OF WEAPONS, INCLUDING MISSILES AND MISSILE SECTIONS DURING SHIPBOARD HANDLING AND STORAGE."

    3. Requirements for an Adequate Electrostatic Ground.
    . . . As a safety precaution the resistance shall not exceed one hundred thousand (100,000) ohms. For areas having non-skid coatings the resistance measured between deck coating and metal deck itself (ship's structure) shall not exceed one hundred megohms . . .

- In a letter, 09E3/JWG, dated 6 July 1979, from the Commander, Naval Air Systems Command, to the Commander, Naval Sea Systems Command (SEA-04H), the following addition to "OP-5 Volume I – Ammunition and Explosives Ashore Safety Regulations" was recommended:

  > During aircraft loading/down loading evolutions involving ordnance, the aircraft shall be grounded. An aircraft ground for purposes of this paragraph is any ground in which the resistance between the aircraft structure and ground is 10,000 ohms or less.

- 4 April 1978, R041707Z Apr. 78, FM:COMNAVAIRSYSCOM, Wash., D.C., Directive eliminating requirement for grounding while fueling:

  > The connection of a static cable to ground is no longer required. . . . This policy change only applies to aircraft fueling/defueling operations and does not affect directives for grounding in aircraft servicing or maintenance operations.

- 12 April 1978, R122153Z Apr. 1978, FM:COMNAVAIRPAC, San Diego, CA, TO:COMNAVAIRSYSCOM, Wash. D.C., referencing COMNAVAIRSYSCOM-R04170Z-Apr. 78 (above):

  > There appears to be a basic inconsistency in policy which eliminated the requirement for static grounding during proven hazardous fueling/defueling operations while still requiring it for more routine servicing and maintenance evolutions. It is requested that early clarification of this problem be provided to enable this type of commander to provide proper and consistent guidance to subordinate units.

2.9 Incident Reports. The investigation utilized incident reports to: (a) estimate the extent of a particular type hazard and (b) survey opinions and recommendations generated at the operational level. It is recognized that there is often only a limited investigation prior to the incident report and often the cause of an incident is obliterated in the ensuing damage. Therefore, in no cases are these reports used as a basis for the technical requirement established through the investigation; they are cited only as supporting factors. In no incident cited below is it a proven fact that grounding, in itself, would have prevented the incidents. However, it is a fact that grounding will eliminate any potential between the aircraft surface and grounded objects, thereby eliminating a major contributing factor in hazardous situations.

The realization of destructive potential illustrated below is a major reason for the inclusion of these report summaries herein. They illustrate the magnitude of the danger to personnel and equipment and the need to reduce all risk factors to a practical minimum.

2.9.1 Parking.

- 20 November 1979, Tulsa, OK, American Airlines, Boeing 707 aircraft, lightning strike: Ground crewman killed when parked aircraft was struck by lightning. Crewman was wearing headset connected to aircraft by wire lead. Facilities Manager stated that aircraft was not grounded.

- 6 August 1974, UR Ident. 74080643601, Model C009B, Buno 159117: Aircraft was struck by lightning and gave an electric shock to a flight attendant who was touching aircraft while standing on the ground. No grounding wires on aircraft.

2.9.2 Maintenance.

- 5 February 1979, R051152Z Feb. 79, FM:COMNAVAIRPLANT Norfolk, VA, Aircraft and GSE Static Electric Ground Problems: Two incidents cited in which aircraft maintenance personnel received electrical shocks when touching aircraft surface during maintenance. Investigation reported that lack of established static ground points provides potential for serious damage and hazard to personnel. Also, there are many disparities in the various documents relating to static grounds for aircraft and GSE. Summary: Most documents pertaining to aircraft/GSE grounding and bonding are outdated and conflicting in many ways. Operators are uncertain as to which is the correct way to ground aircraft and equipment.

2.9.3 Ordnance. A review of 27 USN incidents involving ordnance that were reported between 1963 and 1977 showed the following data:

- Incidents ashore ...... 21 – Involving aircraft 6

- Incidents aboard ...... 6 – Involving aircraft 2

- Of the eight aircraft incidents, suspected causes included the following:

  Static electricity 2

  Electrical equipment problems 3

  Electromagnetic radiation 1

  Lightning 1

  Unknown 1

- In one of the static electricity cases, lack of an aircraft ground was reported to be the prime reason for the accident.

- Of the 19 incidents not involving aircraft, suspected causes included the following:

  Static electricity 14

  Electromagnetic radiation 2

  Lightning 1

  Unknown 2

- In three of the static electricity cases, a lack of grounding was cited.

- 19 February 1970, 021970, Accident/Incident Data Bank, NSWC, Dahlgren, VA. Inadvertent firing of MK-1 Squib during preparation of MK-44 torpedo: Squib fired when technician was removing shorting clip from squib terminal block. Cause: Unknown, possible initiation by static electricity. Technician and torpedo were not statically grounded at the time of explosion.

2.9.4 Fueling/Defueling.

- 26 January 1979, R261107Z Jan. 79, FM:NARF Norfolk, VA, A-6/EA-6 TMS Static Electric Ground Problems: Investigation of an A-6 Fuel Cell explosion attributed to static electricity. Lack of adequate grounds on aircraft to ensure positive ground. Aircraft was not grounded and aircraft attach point was not free of paint. Therefore, grounding operation was probably ineffective. In view of the potential for serious damage and hazard to personnel, urged immediate ECP action to correct deficiencies and A-6/EA-6 TMS omissions.

- 26 October 1978, 781026UEBL002, Gnd. Mishap Data, Richards-Gebaur AFB, MO: Marine Corps A-6E center fuselage fuel tank exploded while being refueled. No injuries, damage of $160,000 to aircraft. The grounding was accomplished by attaching one clip to T-1 ramp ground rod and other clip to nose wheel arm drag link. There is no designated grounding point on aircraft. (This message also indicated the aircraft ground was questionable. However, an additional message relating to this incident, 07143Z NOV 78, from NRL, disputes the assertion of poor grounding.)

- 4 May 1978, Trip Report, jtw/45092, 101st Airborne Div., Ft. Campbell, KY, 18-19 April 1978: Trip was made to investigate rotary wing aircraft refueling fire to determine if static electricity may be possible cause. Findings: Upon landing, the aircraft was grounded with an alligator clip. Charges could have been generated by aircraft or by the fuel. The undercarriage is a painted surface and it is questionable that there was an adequate bonding surface obtained. Conclusions: Static electricity cannot be definitely established or ruled out as source of ignition for the refueling fire. Conclusions: The design of a plug and jack bonding system should be considered to replace the use of alligator clips in grounding the aircraft.

- 20 November 1977, UR Ident. 77112040401/2, Model RF008G, Buno 146883/146827: Fuel truck exploded engulfing 2 RF-8G's in flame. Both aircraft were destroyed. Defueling truck's static ground was attached to tailpipe of Buno 146827. Five persons injured. Suspect static ignition due to switch loading and splash filling were contributing factors. Aircraft and truck were not grounded to earth.

2.10 Cost Considerations. A rough engineering estimate of the cost considerations involving various airframe ground systems was made to avoid recommendations with prohibitive cost penalties. Estimates established for the installation of present grounding systems are as follows:

a. For a grid system (all ground points connected by heavy gage cable):

new	$1.50 per square yard of surface area
retrofit	$3.00 per square yard of surface area

b. For individual rod systems:

new	$55.00 per rod
retrofit	$75.00 per rod

It is further estimated that an individual ground rod can service 100 square yards of apron area. Therefore, on an area basis, the individual ground point costs are cost per rod/100 square yards or:

new	$0.55 per square yard of surface area
retrofit	$0.75 per square yard of surface area

Hence, the rods are generally one-third the price of a grid system and were the most common type ground encountered during the survey.

Addressing the recommendations of this report, the use of mooring padeyes would result in saving of the full installation costs (new or retrofit, grid or rod) for any type grounding system in all areas except where an external power system might be connected to the aircraft.

The higher impedance of the ground rods makes them unsatisfactory for power/maintenance area grounding. A cable system, hard wired back to the power system neutral in a manner capable of sustaining fault current loads, provides an adequate power/maintenance ground. Therefore, a cable grid, as just defined, is the preferred approach in any area where an external power system with an earthed neutral could be used on an aircraft.

In all other cases, use of the mooring padeyes saves the full installation (new or retrofit) costs. It would be easily accomplished on an estimated 85% (area requiring only static grounds) of a typical base. The remaining maintenance areas, approximately 15%, require a ground system capable of sustaining fault current levels (i.e., a grid system). In most cases, an assumed 80%, the necessary grid system is in place. Therefore, in only 2 or 3% of shore base areas would any additional costs be incurred by requiring a cable grid system hard wired to the power system ground for maintenance areas.

The proposed static grounding requirement would also provide an additional savings in ground system maintenance requirements. A 10-kilohm maximum electrical resistance for static ground will eliminate much of the present extensive monitoring or rework efforts required to maintain grounds at the presently required 10- or 25-ohm level.

2.11 Areas of Concern. Areas only indirectly relevant to electrical grounding requirements were encountered during the investigation. No conclusions will be drawn in these areas; however, the particular concerns and data which relate to electrical/aircraft safety are reported below.

2.11.1 Power System Grounding Design. A low impedance ground path is necessary to ensure that protective circuit devices trip when external power is short circuited to the airframe (ground fault). The static ground requirement of 10,000 ohms is entirely inadequate for this type of grounding. Furthermore, the 10- and 25-ohm levels set by facilities design requirements are limited to low power or, at most, average power level situations.

If a 100-ampere, 220-volt service were considered as a worst case example, safety ground impedance must be maintained less than 0.5 ohm to trip circuit protective devices (paragraph 2.6.9). Only a wire grid tied directly to the power ground of the external system could satisfy this requirement. Moreover, if the impedance of the power source cables or grounding contacts were 0.5 ohm, circuit protective devices may still not trip and a hazardous situation could still exist.

A similar problem exists for carrier-based aircraft since the aircraft mooring points, presently considered standard grounding points, are often covered with nonskid epoxy. To ensure adequate grounding, it is required that all padeyes be free of insulating coating. The use of epoxy creates an area of concern for both power and static grounding. It is also required that a positive grounding system be applied in the form of a grounding cable or similar device for connection to the padeye. Tiedown chains are not adequate, as shown by survey measurements.

Thus, the power ground design can be a source of potential hazards. To resolve this problem, a positive low impedance system is required or, at a minimum, a signal warning when a ground fault exists and the circuit breakers have failed to operate.

The servicing of more than one equipment on the same power line further complicates power ground situations. For example, during the survey of NATO facilities it was noted the RAF has developed a trip relay which will disconnect power to the system in the event of a current above 10 milliamps in the ground wire. The purpose of this device, however, is defeated if two aircraft are fed in parallel from a splitter box. Informal communication between the RAF and their USAF counterparts in England shows that it is not an uncommon USAF experience for ground wires to burn. This is used as the fault indicator for a power problem. There is evidence from message traffic that similar problems have occurred on USN aircraft. Further circuit modifications of splitter boxes by the RAF are in development because at present nuisance trips and parallel power feeds make the device impractical.

It is recommended that the area of aircraft grounding for power fault safety be investigated further.

2.11.2 Fuel Additives. The use of fuel additives reduces the charge buildup in the fueling system by increasing fuel conductivity. Several types of additives have been approved for USAF use, and the presence of additives in non-naval supply systems has become widespread. This approach is especially attractive since it resolves the problem of explosions internal to the fuel tank, an area where grounding is ineffective.

A number of questions on the effects of the additives, however, have not been fully answered. The areas of long-term effect on engine operation, low concentration enhancement of arcing, and possible changes in exhaust plume conductivity with related effects on radar cross-section have all been questioned. It is recommended that the use of conductive additives be investigated either to incorporate them into the Navy supply system or, if they are found unsatisfactory, to establish safety procedures for situations such as refueling naval aircraft at non-Navy bases using the additives.

2.11.3 Semi-Conductive Fuel Hoses. The Royal Navy is investigating bonding during the fueling/defueling evolution using a semi-conductive hose. This experiment, a three-phase test program funded by the Royal Navy, is being conducted at Southampton University, United Kingdom. The first phase, which is in progress, consists of making measurements on a fully instrumented fuel supply tank, pump, filter, hose, and receiving tank system. The resistivity of this hose is 10^3 to 10^6 ohms/meter. Presumably the use of this hose would reduce the voltage levels at the aircraft end of the hose with respect to the fueling system and would provide a more dependable, automatic bonding method. It would also provide a considerable simplification in helicopter in-flight refueling evolutions. It is recommended that this effort be monitored to evaluate its effectiveness for US Navy use.

2.11.4 Nonmetallic Fuel Tanks. In-flight lightning strikes pose the major hazard to nonmetallic fuel tanks. However, the use of nonconductive materials also aggravates the problem of charge accumulation within the fuel by preventing or limiting bleedoff. Various protective measures, such as flame-sprayed aluminum coatings on the tank's inner surface, have been introduced. However, considerable contention still exists on the effectiveness of these techniques.

The German Ministry of Defense (MOD), Munich, stated that they would not approve the use of composite material auxiliary fuel tanks on the Multi-Role Combat Aircraft (MRCA) as proposed by the British. Their concern was motivated by the German experience with the French Magister aircraft. They further claimed that the use of flame-sprayed aluminum metal strips did not alleviate the hazardous condition. The British MOD experience seemed to refute this. For example, the RAF Jet Provost aircraft had seven lightning strikes on plastic wing tanks, which resulted in five explosions; since protective conducting strips have been applied to the plastic tanks, no further explosions have occurred.

No positive consensus of opinion has been obtained concerning the use of composite materials. It is therefore recommended that an engineering investigation resolve the question of hazards in this area for Navy use.

2.11.5 R.F. Arcing. This hazard occurs in a high-level ambient radio frequency electric field when conducting surfaces are established with the proper geometry to intercept and channel the r.f. energy. A common situation is carrier deck operations near a high-power operational radio antenna. Grounding chains establish a conducting loop of chain, deck, and aircraft which intercepts r.f. energy and causes arcing of a level sufficient to be hazardous to personnel, to ignite a proper air-fuel vapor mix, to trigger electro-explosive devices, or to damage sensitive electronic components.

Grounding would, in general, produce a slight improvement in the configuration. Unfortunately, in almost as many cases grounding could establish the proper geometry (i.e., a conductive loop) to intercept large amounts of r.f. energy. In such cases, disturbing the configuration by removing chains (breaking the loop) almost guarantees arcing. Hence a solution using grounding to eliminate the r.f. hazard becomes extremely involved. Action is required in this area. A full investigation of the r.f. arcing problem and the implementation of an effective and practical procedure to ensure safe operation in high-energy fields are needed as soon as possible. It is recommended that the Navy perform investigations in these areas to establish the required procedures.

3.0 CONCLUSIONS AND RECOMMENDATIONS.

3.1 General Conclusion. The program efforts have established that there are valid technical reasons to electrically ground aircraft for all evolutions, including all aspects of maintenance, fueling, stores handling, and parking. The electrical grounding requirement is a single, simple standardized requirement that will pertain to all aircraft types. Only in the case of extenuating circumstances (e.g., extreme adverse ground cover, etc.) might an evaluation by NAVAIRSYSCOM determine that the technical reasons for grounding no longer pertain and, therefore, that administrative requirements for aircraft electrical grounding may be waived.

3.2 Specific Conclusions and Recommendations.

3.2.1 Static Ground Configuration. Aircraft static electrical grounds of 10,000 ohms or less are required during all aircraft evolutions including park to ensure personnel and equipment safety (paragraphs 2.6.9 and 2.7). Measurements of aircraft mooring points have averaged 2,000 ohms to ground (Tables VI and IX, pages 28 and 31) and, therefore, mooring points are adequate as static electrical points. In any case not involving an external power system the airframe may be static electrically grounded either to the existing installed ground system or to the aircraft mooring point, whichever is more convenient. In new installations the aircraft mooring point resistance to earth should be verified as less than 10,000 ohms. Thereafter the mooring point will serve as an adequate static ground. No other static grounding system is required.

3.2.2 Power Ground Configurations. No single return impedance can be set for a power ground system (paragraphs 2.6.9 and 2.11.1). The present power system design practice of connecting airframe and power neutral requires differing values for various fault protection levels. However, a maximum impedance of 0.5 ohm between generator neutral and airframe grounding point is satisfactory for most operations using a grounded neutral system. Therefore, 0.5 ohm is recommended as a standard value for ground point resistance to power system neutral with the proviso that calculations and measurements be made to ensure ground point resistance adequacy for any service loads greater than 60 amperes.

Connection to a ground point meeting the power ground level of 0.5 ohm is required preparatory to the introduction or connection of power or test cables to the aircraft if a grounded neutral power distribution system is involved.

In terms of mobile power (neutral not tied to a grid system), the power cart frame need only be bonded to the aircraft structure to ensure ground fault protection for personnel and equipment. However, in all cases involving more than one structurally separate system (e.g., aircraft and fuel truck or aircraft and mobile power cart), there is a very real chance that bonding between systems will not be successful. As with any other configuration where single-point failures may occur, the triangular combination of bonding and grounding should be employed to ensure redundant paths and reduce risks.

3.2.3 Aircraft Mooring or Tiedown Chains. The impedance of aircraft mooring or tiedown chains varies over a wide range (paragraph 2.6.6) and, therefore, is not adequate to provide static or power ground. It is concluded that a positive low-impedance ground path is required in addition to tiedown chains.

3.2.4 Documentation. The present documentation is complex, confusing, and contradictory (paragraph 2.8). A grounding handbook is required to: (a) provide the necessary technical background to develop procedures at the operational level, (b) establish design and test techniques, (c) specify all grounding requirements for each unique aircraft type and (d) alert and inform operations personnel of all known grounding-related hazards to electronic equipment and to ordnance associated with specific aircraft.

3.2.5 Recommendations for Further Investigation. While the objectives of the original Airframe Electrical Grounding Requirements Program have been accomplished, implementing further investigations as recommended herein will have a significant effect in further improving naval air safety. The specific areas to be addressed are:

a. Power system ground design (paragraph 2.11.1)

b. Fuel additives (paragraph 2.11.2)

c. Semi-conductive fuel hoses (paragraph 2.11.3)

d. Nonmetallic fuel tanks (paragraph 2.11.4)

e. R.F. arcing (paragraph 2.11.5)

4.0 SUMMARY OF SURVEY DATA

4.1 Measurement Data. The following tables summarize data obtained during the various surveys identified in paragraph 5.3. It should be noted that the data recorded were representative samplings of parameters at the facilities visited and do not provide the absolute maximum and minimum values existing at these facilities. The data were used to obtain an average of the values and the variations in these values.

4.2 List of Tables. The data are presented as follows:

Table IV

Resistance of Aircraft to Ground (No Ground Cable Attached)

Location	$\bar{x}$ (Ω)	σ (Ω)	Sample Size = n	Min. (Ω)	Max. (Ω)
CONUS					
MCAS, Cherry Point, North Carolina	403k	301k	6	20k	1M
NAS, Pensacola, Florida	251.3k	277.3k	19	15k	1M
NAS, Brunswick, Maine	–	–	2	30k	160k
MCAS, Yuma, Arizona	26M	13M	3	9M	40M
NAS, Miramar, California	372k	445k	3	17k	1M
NAS, Whidbey Island, Washington	11.6k	6.8k	5	2k	20k
AFB, Kelly, Texas	9.1k	7.6k	8	1k	27k
AFB, Richards-Gebaur, Missouri	–	–	1	4k	4k
Range	–	–	–	1k	40M
NON-CONUS					
NAVSTA, Adak, Alaska	–	–	1	4k	4k
NAS, Barbers Point, Hawaii	10k	5k	7	4k	20k
Range	–	–	–	4k	20k

$\bar{x}$ – Mean
σ – Standard Deviation

Table V

Resistance of Grounding Points – In Hangars

Location	$\bar{x}$ (Ω)	σ (Ω)	Sample Size = n		Min. (Ω)	Max. (Ω)
CONUS						
NATC, Patuxent River, Maryland	6.5	0.5	4		5.6	6.9
MCAS, Cherry Point, North Carolina	0.24	0.07	7		0.19	0.37
NAS, Pensacola, Florida	3.34	3.86	5		0.40	10.30
NAS, Brunswick, Maine	445	358	11		167.0	1450.0
MCAS, Yuma, Arizona	0.37	0.17	9		0.17	0.59
NAS, Miramar, California	0.37	0.11	9		0.30	0.63
NAS, Whidbey Island, Washington	3.1	3.3	29		0.25	9.30
AFB, Kelly, Texas	0.74	0	3		0.74	0.74
AFB, Richards-Gebaur, Missouri	–	–	2		0.19	0.19
Range	–	–	–		0.17	1450.0
NON-CONUS						
NAVSTA, Adak, Alaska	0.81	0	4		0.81	0.81
NAS, Barbers Point, Hawaii	225.7	211.7	14	Old Hangar	5.2	637
				New Hangar	0.71	2.7
NAF, Midway Island	4.26	2.06	13		0.40	18.7
Range	–	–			0.40	637

$\bar{x}$ – Mean
σ – Standard Deviation

Table VI

Resistance of Aircraft Mooring Points

Location	$\bar{x}$ (Ω)	σ (Ω)	Sample Size = n	Min. (Ω)	Max. (Ω)
CONUS					
NATC, Patuxent River, Maryland	92.3	72.0	5	36.0	230.0
MCAS, Cherry Point, North Carolina	–	–	1	750.0	750.0
NAS, Pensacola, Florida	226	44	3	191.1	288.0
MCAS, Yuma, Arizona	157	88.4	4	160.0	289.0
NAS, Miramar, California	357.8	334.0	11	78.0	940.0
NAS, Whidbey Island, Washington	284	119	3	166.0	447.0
Range	–	–	–	36.0	940.0
NON-CONUS					
NAVSTA, Adak, Alaska	–	–	2	0.88	690
NAS, Barbers Point, Hawaii	151.2	133.3	23	0.41	595
NAF, Midway Island	75.04	40.2	62	0.47	298
Range	–	–	–	0.41	690

$\bar{x}$ – Mean
σ – Standard Deviation

Table VII

Resistance of Grounding Points – Outside

Location	$\bar{x}$ (Ω)	σ (Ω)	Sample Size = n	Min. (Ω)	Max. (Ω)
CONUS					
NATC, Patuxent River, Maryland	7.8	6.4	8	1.6	20.2
MCAS, Cherry Point, North Carolina	36.5	30.3	16	0.85	88.8
NAS, Pensacola, Florida	16.7	20.8	5	1.55	54.5
NAS, Brunswick, Maine	16.2	20.1	11	3.0	58.0
MCAS, Yuma, Arizona	16.3	11.1	9	3.6	32.6
NAS, Miramar, California	41.7	78.1	12	0.89	286.0
NAS, Whidbey Island, Washington	6.6	6.2	22	0.39	30.6
AFB, Kelly, Texas	15.0	8.5	15	5.7	32.9
AFB, Richards-Gebaur, Missouri	39.8	11.1	4	21.3	51.0
Range	–	–	–	0.39	286.0
NON-CONUS					
NAVSTA, Adak, Alaska	0.93	0.33	4	0.6	1.3
NAS, Barbers Point, Hawaii	37.4	74.2	23	0.47	224
NAF, Midway Island	349.9	292.7	23	0.39	988
Range	–	–	–	0.39	998

$\bar{x}$ – Mean
σ – Standard Deviation

Table VIII

Data Summary – Carrier (CVN-69)

A – no tiedown chains on aircraft

Aircraft Type	$\bar{x}$ (Ω)	σ (Ω)	Sample Size = n	Min. (Ω)	Max. (Ω)
A-7E	2.24M	1.8M	7	80k	5M
EA-6	1.2M	1.3M	3	0.6M	3M
A-6E	–	–	2	0.04M	4M
KA-6D	–	–	1	1M	1M
S-3A	0.4M	0.43M	3	15k	1M
F-14	2.0M	2.0M	6	0.4M	100M

B – with tiedown chains attached

Aircraft Type	$\bar{x}$ (Ω)	σ (Ω)	Sample Size = n	Min. (Ω)	Max. (Ω)
A-7E	177	301	4	0.7	700
S-3A	0.8	0.78	5	0.46	20
KA-6D	–	–	2	1.8	970
EA-6B	–	–	2	5.0	500
F-14	2.7k	4.2k	4	0.5	40k
A-6E	205	344	4	0.3	800
SH-3H	1.37k	492	3	800	2k

Note: Tiedown chains removed from aircraft and single chain resistance measured:

(1) Full length – 5 megohms (using 1000V megger)
(2) 10 links – 4 megohms

$\bar{x}$ – Mean
σ – Standard Deviation

Table IX

Data Summary of European Facilities

Location	$\overline{x}$ (Ω)	σ (Ω)	Sample Size = n	Min. (Ω)	Max. (Ω)
	Resistance of Grounding Points – Outside				
NAS, Valkenberg, Netherlands	5.2	2.2	12	1.0	7.7
AFB, Neuberg, Germany	2.5	3.3	12	0.7	10
AFB, Gioia Del Colle, Italy	472.9	687.6	11	0.7	2350
Dornier, Germany	–	–	1	8.1	8.1
	Resistance of Grounding Points – In Hangar				
NAS, Valkenberg, Netherlands	6.3	1.6	4	5.1	9.0
AFB, Neuberg, Germany	2.5	3.3	12	0.7	10.0
AFB, Gioia Del Colle, Italy	1.0	0.3	6	0.6	1.4
	Resistance of Aircraft Mooring Points				
NAS, Valkenberg, Netherlands	205	74	7	124	350
	Resistance of Aircraft to Ground (No ground cable attached)				
NAS, Valkenberg, Netherlands	–	–	2	4.4	100k
AFB, Neuberg, Germany	17.5M	17.8M	4	15k	40M
AFB, Gioia Del Colle, Italy	172k	168k	6	16k	400k
Reim, Germany	–	–	1	1k	1k
Dornier, Germany	–	–	2	15k	15k

Resistance of weapons cart to ground – (Special surface at refueling area in Neuberg, Germany) 2000 megohms

$\overline{x}$ – Mean
σ – Standard Deviation

Table X

Summary of Naval Airbase Questionnaire

In order to obtain field activity inputs to provide a necessary data base for analysis of operating conditions for aircraft grounding, the following bases were contacted:

1. NAS, Alameda, California
2. NAS, Chase Field, Texas
3. NAS, Corpus Christi, Texas
4. NAS, Fallon, Nevada
5. NAS, Glenview, Illinois
6. NAS, Jacksonville, Florida
7. NAS, Kingsville, Texas
8. NAS, Lemoore, California
9. NAS, Meridian, Mississippi
10. NAS, Norfolk, Virginia
11. NAS, Oceana, Virginia
12. NAS, Whiting Field, Florida
13. NAS, Point Mugu, California
14. NAVFAC, San Nicolas Island, California
15. NAVSTA, Mayport, Florida
16. NAVSTA, Keflavik, Iceland
17. MCAF, Camp Pendleton, California
18. MCAS, Quantico, Virginia
19. MCAS, El Toro, California
20. MCAS, New River, North Carolina
21. NAS, Moffett Field, California
22. NAS, North Island, California
23. Antarctic Development Squadron Six – VKE-6

Summary of Naval Airbase Questionnaire
(In percentages)

No. Stations Responding	Bond & Ground During Fueling	Bond Only During Fueling	Ground for Ordnance Loading	Use JP-4	Use JP-5
23	82%	18%	95.5%	56.5%	65.25%

(See Volume II for details)

Table XI

Summary of Specific Airframe Electrical Characteristics at NAEC

DATA

1. Data Summary of Parameter Extremes

	Min.	Max.
Resistance Measurement (arresting hook up)	5kΩ	20MΩ
Capacitance Measurement (acrylic under wheels)	1.5 nf	5.1 nf

2. Static Voltage During Fueling TA-4

Static Voltage	Remarks
+600V to -600V	Positive to negative varied with a period of about 1 second at 60 gpm fuel rate, 0.5 second at 120 gpm rate.
-2500V	Removed ground after refuel and waited approximately 2 minutes before reading. TA-4 was isolated by acrylic sheets under wheels.

3. DC Measurements During TA-4 Fueling

	DC Level At 60 gpm	At 120 gpm	At 400 gpm*
Current in Bonding Wire	0.8 μA	1.4 μA	7.5 μA
Current in Grounding Wire	0	0	–

*This measurement taken at Kelly AFB on an F-4 aircraft.

5.0 PROGRAM PARTICULARS.

5.1 Program Tasks. The Airframe Electrical Grounding Requirements Program investigated the technical grounding requirements for various aircraft evolutions, the status of present electrical grounding standards and requirements, and the interrelationship with basic electrical grounding parameters. The investigation included operations presently being performed in the fleet, at naval airbases and at non-naval facilities such as US Air Force and NATO bases. New techniques and technology applicable to electrical grounding were investigated.

5.2 Program Elements. Major elements of the program included:

a. Aircraft grounding requirements literature survey

b. Technical literature survey

c. Field/Equipment survey

d. R&D survey

e. Liaison

f. Technical review

g. Reports

5.3 Element Subdivisions. Each of the above elements was further defined as follows.

5.3.1 Aircraft Grounding Requirements Literature Survey. This activity involved the survey of technical publications pertaining to existing electrical grounding requirements. Investigated were:

a. Navy Instructions

b. Navy Regulations

c. Aircraft Technical Manuals

d. Safety Standards

e. NAVOPS, NAVMAT Directives and Publications

f. Incident Reports

g. Applicable Design Standards, MIL-STDs, and MIL Specifications

5.3.2 Technical Literature Survey. This activity searched and documented available technical literature pertaining to the program. Documents searched included:

a. Technical papers

b. Test reports

c. Position papers

5.3.3 Field Survey. The field survey activities provided an engineering review of the operating conditions and requirements for aircraft grounding. Diverse climatic and functional conditions were encountered. The following locations were surveyed:

a. NATC, Patuxent River, Maryland

b. MCAS, Cherry Point, North Carolina

c. NAS, Pensacola, Florida

d. NAS, Brunswick, Maine

e. MCAS, Yuma, Arizona

f. NAS, Miramar, California

g. NAS, Whidbey Island, Washington

h. AFB, Richards-Gebaur, Missouri

i. AFB, Kelly, Texas

j. NAVSTA, Adak, Alaska

k. NAS, Barbers Point, Hawaii

l. NAF, Midway Island

m. NAEC, Lakehurst, New Jersey

n. NATO Bases

o. Carrier Facility – USS Dwight D. Eisenhower (CVN-69)

p. Naval Airbases (see Table X)

5.3.4 R&D Survey. A number of research facilities were surveyed and the techniques and philosophies reviewed. Facilities visited and/or contacted were:

a. Shell Research Ltd.

b. Naval Research Laboratory (NRL)

c. National Bureau of Standards (NBS)

d. Aviation and Petroleum Industry Research Centers

5.3.5 Liaison. Interfaces were established with other agencies such as:

a. US Air Force

b. US Army

c. North Atlantic Treaty Organization (NATO)

d. Air Standards Coordinating Committee (ASCC)

5.3.6 Technical Review. All data obtained in previous phases of the program were reviewed with the objective of arriving at technical requirements and conclusions as required. The following areas were reviewed:

a. Grounding requirements literature

b. Technical literature

c. Field survey reports

d. R&D data

e. Liaison reports

f. Incident reports

5.3.7 Reports. Reports were issued to provide internal program communication and final program output:

a. Periodic Reports

b. Working Group Minutes

c. Trip Reports

d. Field Survey Reports (Interim Data)

e. Final Report

5.3.8 Working Group. A technical working group was organized consisting of members of various organizations as listed in Table XII. The function of this group was to:

a. Perform designated tasks as required by the major elements of the program

b. Perform tasks as assigned at periodic working group meetings

c. Meet periodically to review results

d. Submit a final report detailing data obtained and establishing technical requirements

Table XII

Executive Committee and Working Group Members

Activity	Responsibility	Contact
NAVAIRSYSCOM/EM Technology AIR 5162G4	Program Management Working Group Leader Field Survey	A. J. Iacono
NAVAIRSYSCOM/Armament AIR 54122A	E^3 – Armament Interface Working Group Member Field Survey	D. R. Ballard
NAVAIRSYSCOM/Design Safety (Hero) AIR 5162D	Ordnance Safety Working Group Member	D. Fellin
NAVAIRSYSCOM/Design Management 512C	Working Group Member	J. T. MacLaughlin
NAVAIRSYSCOM/Flight Mechanics and Fluid Management AIR 530313C	Work Group Member	W. McMillan
NAVAIRSYSCOM AIR 5162F	Working Group Member Grounding Components Requirements	J. H. Snider
NSWC/DL/Hero DF52	Hazards of Electromagnetic Radiation to Ordnance Testing	W. Lenzi
NATC/SY87	E^3 Testing	R. Hammett
NAEC/Test Department Systems Division 945	Working Group Member Field Survey Evaluation and Reports	V. Tukiendorf
NADC/E^3 Program Office 20P3	Working Group Member E^3 Design	W. Walker
Dayton T. Brown, Inc. Labs/ EMC SECT	Working Group Member E^3 Engineering Electromagnetic Vulnerability Field Survey	T. Mahoney
COMNAVAIRLANT/526	Liaison Fleet Operations	F. Orr
NSWC/DL-N42	Liaison National Fire Protection Association Committee	M. Guthrie
NAVFAC/0441D	Facilities Liaisons	M. Worden
NAVSEA/04H3	Liaison NAVSEA	G. Heimer
NAVELEX/51032	Liaison NAVELEX	C. Neil

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GLOSSARY

AFB	Air Force Base.
ASA-3	Conductive Fuel Additive, Shell Oil Company.
ASCC	Air Standards Coordinating Committee.
BONDING	An electrical connection used to join two metallic structures.
BUNO	Bureau Naval Aircraft Number.
BWB	Bundesant für Wehretechnik and Beschaffung.
COMNAVAIRLANT, AIRLANT	Commander, Naval Air Atlantic, Norfolk, Va.
COMNAVAIRPAC, AIRPAC	Commander, Naval Air Pacific, San Diego, Calif.
CONUS	Continental United States.
DTB	Dayton T. Brown, Inc., Bohemia, N.Y.
E^3	Electromagnetic Environmental Effects.
EED	Electro-Explosive Device.
EM	Electromagnetic.
EVOLUTION	Any operation performed on an aircraft.
EXTERNAL POWER	Power applied to an aircraft via external sources.
GROUND POINT	The point, assumed to be at earth potential, to which a ground cable is attached.
GROUND RECEPTACLE	The receptacle permanently mounted on the aircraft into which a ground cable plug is inserted.
GROUNDING	Attaching a cable on wire between an aircraft and an approved grounding point (earth).
GSE	Ground Support Equipment.
HERO	Hazards of Electromagnetic Radiation to Ordnance.

IAF	Italian Air Force.
MAINTENANCE POWER GRID	A grounding system with an electrical connection to the power system neutral.
MCAF	Marine Corps Air Facility.
MCAS	Marine Corps Air Station.
MIL-STD	Military Standard.
MOD	Ministry of Defense.
MOORING EYE	A point to which a tiedown chain or ground strap is attached. See PADEYE.
MRCA	Multi-Role Combat Aircraft.
NADC	Naval Air Development Center, Warminster, Pa.
NAEC	Naval Air Engineering Center, Lakehurst, N.J.
NAF	Naval Air Facility.
NARF	Naval Air Rework Facility.
NAS	Naval Air Station.
NASC	Naval Air Systems Command, Washington, D.C.
NATC	Naval Air Training Center, Patuxent River, Md.
NATO	North Atlantic Treaty Organization.
NATOPS	Naval Air Training and Operating Procedures.
NAVAIRSYSCOM, NAVAIR	Naval Air Systems Command, Washington, D.C.
NAVELEX	Naval Electronic Systems Command, Washington, D.C.
NAVFAC	Naval Facilities Engineering Command, Washington, D.C.
NAVMAT	Naval Material Command.
NAVOPS	Naval Operations.

NAVSEA	Naval Sea Systems Command, Washington, D.C.
NAVSTA	Naval Station.
NBS	National Bureau of Standards.
NFPA	National Fire Prevention Association.
NON-CONUS	Outside Continental United States.
NRL	Naval Research Laboratory, Washington, D.C.
NSWC/DL	Naval Surface Weapons Center, Dahlgren, Va.
NWEF	Naval Weapons Evaluation Facility, Albuquerque, N. Mex.
OP	Operational Procedure.
ORD	Ordnance.
PADEYE	A point to which a tiedown chain or ground strap is attached. See MOORING EYE.
PARKED	An aircraft upon which no evolutions are being conducted.
POWER GROUND	An approved ground point with an impedance less than 0.5 ohm to the power system neutral.
R & D	Research and Development.
RAE	Royal Aircraft Establishment.
RAF	Royal Air Force.
RED LABEL AREA	A prescribed area on an airfield where loading/unloading of stores on an aircraft takes place.
RF, R.F.	Radio Frequency.
RN	Royal Navy.
SAE	Society of Automotive Engineers.
SPLITTER BOX	An equipment used to supply power to more than one aircraft from a common external source.

STADUS-450	Conductive fuel additive, DuPont Corporation.
STANAG	Standardization Agreement.
STATIC GROUND	An approved ground point that has an impedance of less than 10 kilohms.
TIEDOWN CHAIN	A metal chain used to secure the aircraft to the deck.
TRC	Thornton Research Center.
UK	United Kingdom.
UR	Unsatisfactory Report.
USAF	United States Air Force.
USN	United States Navy.